

DEEP SPACE NETWORK REVITALIZATION - OPERATIONS FOR THE 21ST CENTURY

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Abstract

The National Aeronautics and Space Administration (NASA) supports unmanned space missions through a Deep Space Network (DSN) that is developed and operated by the Jet Propulsion Laboratory (JPL) and its subcontractors. The DSN capabilities have been incrementally upgraded since its establishment in the late '50s and are delivered from three Deep Space Communications Complexes (DSCC's) near Goldstone, California, Madrid, Spain, and Canberra, Australia. At present each DSCC includes large antennas with diameters from 11 meters to 70 meters, that operate largely in S-band and X-band frequencies. In addition each DSCC includes all the associated electronics to receive and process the low-level telemetry signals, and radiate the necessary command with high-power transmitters. To accommodate support of the rapidly increasing number of missions by NASA and other space agencies, and to facilitate maintaining and increasing the level of service in a shrinking budget environment, JPL has initiated a bold road map with three key components:

- 1. A Network Simplification Project (NSP) to upgrade aging electronics, replacing them with modern commercially based components. NSP and related replacement tasks are projected to reduce the cost of operating the DSN by 50% relative to the 1997 levels.*
- 2. Upgrade of all 34-m and 70-m antennas to provision of Ka-Band telemetry downlink capability, complemented by an existing X-band uplink capability. This will increase the effective telemetry downlink capacity by a factor of 4, without building any new antennas.*
- 3. Establishment of an optical communications network to support for high-data-rate unmanned missions that cannot be accommodated with radio-frequency (RF) communications, as well as establish a path toward support of manned missions at Mars.*

In this paper we present the mission loading projected for 1998-2008 and the elements of the JPL road map that will enable supporting it with a reduced budget. Particular emphasis will be on streamlining the architecture and to reduce the DSN cost for operations, maintenance and sustaining engineering while at the same time also simplifying and reducing the operations cost for the flight missions.

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1. INTRODUCTION

The Deep Space Network (DSN) is a collection on antennas and electronic equipment used primarily for communications with and navigation of man-made probes throughout the planetary system. As shown in Figure 1, the DSN consists of three Deep Space Communications Complexes (DSCC) spread in longitude to provide 24-hours continuous coverage, as well as a control center in Pasadena, Ca, and test facilities near Pasadena, CA and Cape Kennedy, FL. In addition to its role in deep space communications and navigation, the DSN is also active in directly collecting science data in the areas of radio-science, radio astronomy, very long baseline interferometry (VLBI) and planetary radar. Though originally developed for deep space applications, the DSN has incorporated since the early '80s a set of 26m antennas, which support Launch and Early Orbit Phase (LEOP), of missions and Highly Elliptical Orbit (HEO) missions. Finally, the DSN capabilities are often used to support Low-Earth Orbit (LEO) missions under unique situations, primarily emergencies.

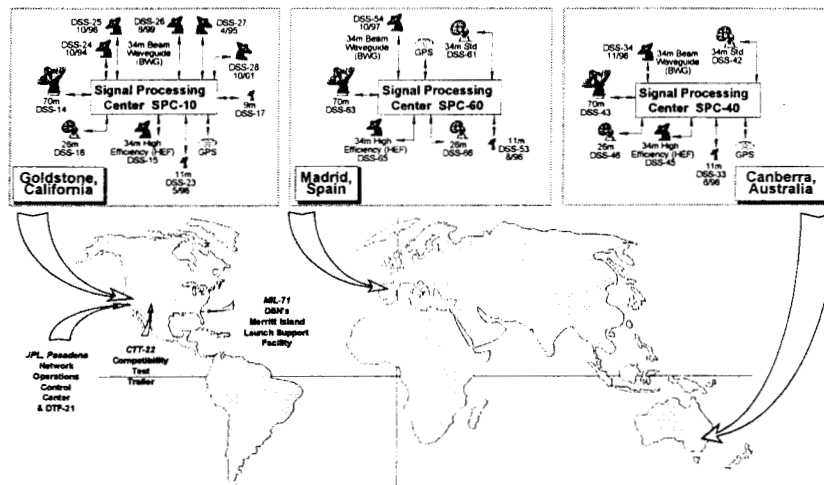


Figure 1 – DSN Configuration

The most visible elements of the DSN are the large Radio Frequency (RF) antennas. Each DSCC has one 70-meters-diameter antenna and several 34-meters-diameter antennas as well as smaller antennas. Due to the unique requirements of the deep space communications link, these antennas are equipped with low-noise amplifiers (usually cryogenic) and high-power transmitters (up to hundreds of KWs). Though initially communicating in the L- and S-band, most deep space communications has migrated to the X-band over time. In addition to the antennas and associated RF equipment, the DSN has unique requirements and equipment in the areas of signal processing for weak signals and stable frequency and timing generation and distribution. The

remainder of the DSN equipment is accommodated via commercial-grade equipment.

Received Signal Sensitivity:

The received energy from Voyager at Neptune, if integrated for 300 million years, would be just enough to set off a small photographic flashbulb!

Received power = 10^{-17} Joules/sec



Command Power:

The DSN puts out enough power in commanding Voyager that it could easily provide high quality commercial TV at Jupiter!

Transmitted power = 400 kW



Dynamic Range of the DSN:

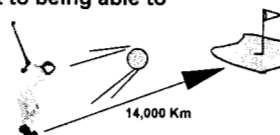
The ratio of the received signal power to the DSN transmitting power is like comparing the thickness of a sheet of tissue paper to the entire Earth!

Ratio = 10^{-27}



Voyager navigation at Neptune is equivalent to being able to tee – off from California and place the ball on a green in Washington, D.C.!

Angular accuracy = 50 nrad



Frequency Stability:

The DSN's ionic clocks used to achieve this navigation accuracy are so stable that only one second of error would accumulate every 30 million years!

Allan variance = 10^{-15} in 1000 seconds



Once-in-a-lifetime Science Opportunities:

The data from a planetary encounter is more valuable than the most rare Earth elements! The reliability of a spacecraft and the DSN together is equivalent to driving an automobile for 3 billion miles without a single failure!



Figure 2 – Unique Characteristics of Deep Space Communications

The DSCC's and the Pasadena Control Center operate continuously, 24 hours per day, 7 days per week. They follow a schedule that is focused largely on operational passes with some maintenance and upgrade times incorporated as needed. NASA has a process that arbitrates the loading on the DSN antennas as the initial support requests from the missions often exceed the DSN capability by 10%-20%.

By the nature of deep space exploration, the DSN has evolved to require customized and expensive operations, at least compared to the operations of LEO missions. Recall that deep space communications and navigation has unique characteristics in terms of detecting sensitivity, accuracy, and so forth, illustrated in Figure 2. Unlike HEO missions, deep space missions are focused on critical phases that must be executed correctly or the mission would risk severe peril or even be lost – orbit insertion, fly-by, sling-shot, etc. There is rarely a chance for a second attempt, and the long round-trip-light-time encourages

careful planning ahead of time, with large teams that monitor and control each of these events to assure its success and take any corrective action. Such customized 24x7 operations are included in the mission cost and can amount to a significant percentage of the total mission cost.

With the heavy loading on antenna time, and the limitations/reductions in operating budget, the DSN had to face the good-news-bad-news environment shown in Figure 3: NASA is launching an ever increasing number of faster-better-cheaper missions. Rather than initiate a single large deep space mission once every several years, NASA is now launching several smaller missions per year – six missions in the 8/98 – 2/99 period alone! JPL is gearing to transform the DSN to accommodate this challenge – reduce operations cost while supporting an increasing number of missions. The next sections describe the three key elements of the JPL road map for the DSN: a Network Simplification project (NSP), transition to Ka-band frequencies, and finally future transition to optical deep space communications.

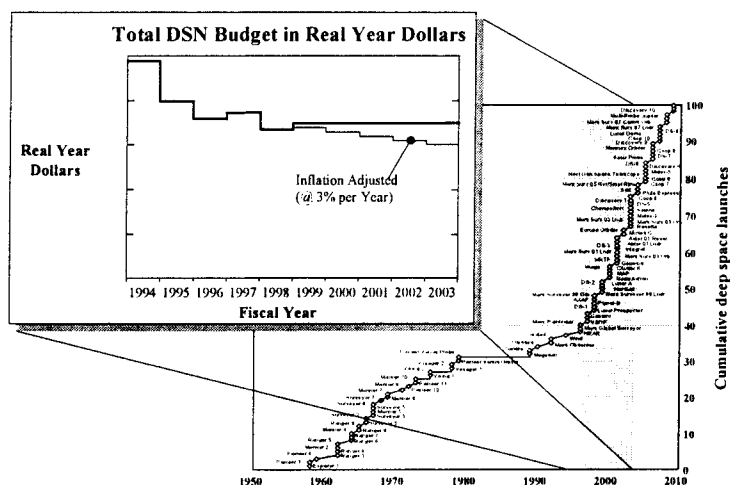


Figure 3 – DSN Loading and Budget

2. NETWORK SIMPLIFICATION PROJECT (NSP)

NSP addresses the issue of reducing the cost of operating the 34-m and 70-m portions of the DSN while maintaining or enhancing current capabilities. There are other activities at the DSN to contain the cost of operating the smaller antennas that are outside the scope of this article.

Let us describe first the operational scenario of a DSCC. Once a tracking pass has been committed through the allocation process, the tracking process consists of four phases:

1. Preparation. In this phase the mission supplies a sequence of events (SOE) and other planning files. The DSN control center prepares all the requisite tracking predicts and directions and transmits them to the DSCC ahead of the tracking

pass. This phase often requires frequent consultation with the mission to assure that the SOE and equipment selection is correct and even optimal.

2. Pre-calibration. Before the tracking pass, a controller in the DSCC assigns required equipment to the antenna, sets all the required configurations, resets as needed, calibrates the delays, allows the transmitter to stabilize, and bring the antenna to point.
3. Tracking. Often the most quiescent phase. During the tracking phase, the antenna tracks the spacecraft and conducts the planned communications and navigation.
4. Post-Calibration. Once the pass is complete, a final calibration is conducted (if needed); then the equipment is de-assigned and the antenna is returned to its stow (vertical pointing) position until the next tracking pass.

Of the four phases, the pre-calibration phase, though short in time, tends to be the most operationally complex. For a typical deep space tracking pass, precal (as precalibration is often called) takes 30-90 minutes, the tracking pass itself lasts for up to 12 hours, and postcal lasts 30-60 minutes. During Precal, operators are required to actively intervene to resolve problems arising from (a) unique and complex equipment, (b) aging and failing equipment, and (c) equipment that is not computer controlled.

NSP (in a broad sense) is focused on addressing problems in areas (b) and (c). When completed, NSP will enable reduction in the need for extensive personnel intervention during precal and postcal, will simplify handling of anomalies during the tracking pass, and will simplify the preparation phase of the tracking pass. By modernizing the DSCC equipment, NSP will also reduce the maintenance cost and the associated sustaining engineering cost. Overall, NSP will reduce the operations cost of the DSN while providing equal or better quality of service to the missions.

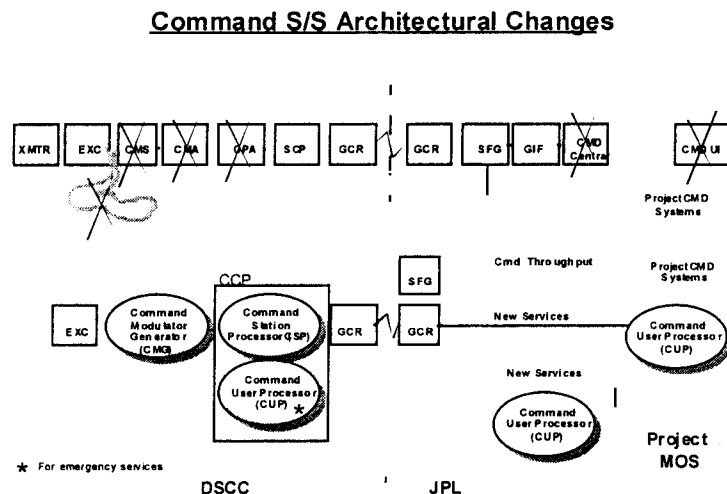
Key components of NSP in the DSCC are:

1. Replace the aging telemetry and command equipment with modern COTS-based equipment, improving the operability and reducing the need for repair and other downtime.
2. Replace the aging ranging and Doppler equipment; merge with the telemetry and command equipment.
3. Reduce the number of switches and controls that require operator intervention.
4. Finally, support the eventual remoting of a significant portion of DSCC operations.

As an example of NSP, let us consider the upgrade of the DSCC command capability. Prior to NSP, commanding required the concatenation of several subsystems, each over 15-year old. A command assembly switch was used to select the "best" command assembly for the present tracking pass. Both the maintenance of the command assemblies and the hand-selection of

equipment for the pass were time consuming and expensive, primarily in terms of personnel. After NSP, a modern module, CMG, will be hard-wired to each uplink exciter. A second module, CCP, will be hard-wired to the CMG. Both the CMG and CCP will be based on either COTS or mature JPL software. In addition, the CCP will incorporate parts of the command software that is presently located at JPL, reducing the cost and complexity of interfacing the DSCC command capability and the JPL command capability. The before-and-after pictorial below illustrates the change.

Figure 4 – Before-and after Pictorial of the DSCC Command Capability



As part of the broader NSP, the DSN will increase the effort to provide computer control to all subsystems in the DSCC's. Some older systems e.g. microwave switches, as well as some mechanical and power components are not presently computer-controlled, requiring manual intervention by station staff. Minimizing these non-computer-controlled functions will allow for the reduction of operations cost via reduction in the size of the operations shifts.

3. UPGRADE TO Ka-BAND RECEPTION

While NSP addresses the issue of reducing the cost of operations, it contributes only marginally to the ability to support additional missions, primarily through reducing the time required for precal, postcal and maintenance.

Over the years, JPL has taken steps to handle the increased tracking time required by the increasing number of missions. These include increasing the efficiency of the communications link via higher frequencies, better error-correcting coding, higher power transmitters, more efficient antennas, and more sensitive receivers, as well as improving the on-board data processing. Nevertheless, in the late '90s the options were narrowed to four practical ones:

- (a) Build additional RF antennas
- (b) Transition to higher frequency RF communications

(c) Transition to Optical communications

(d) Restrict missions' access to tracking time.

JPL and NASA have chosen (b) as the most cost-effective solution in the near-term, with (c) as a viable competitor as technology for the ground and flight system evolves. As shown in Figure 5, JPL has embarked on a plan to upgrade the five DSN Beam Wave guide antennas (3 at the Goldstone DSCC, one at the Madrid DSCC, one at the Canberra DSCC) to Ka-band downlink reception. Following that, additional upgrade to Ka-band reception and to optical communications will be planned.

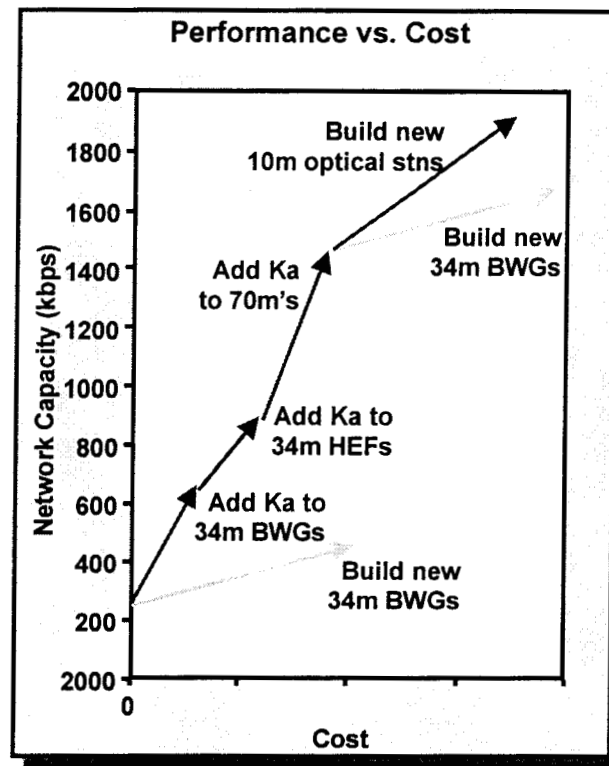
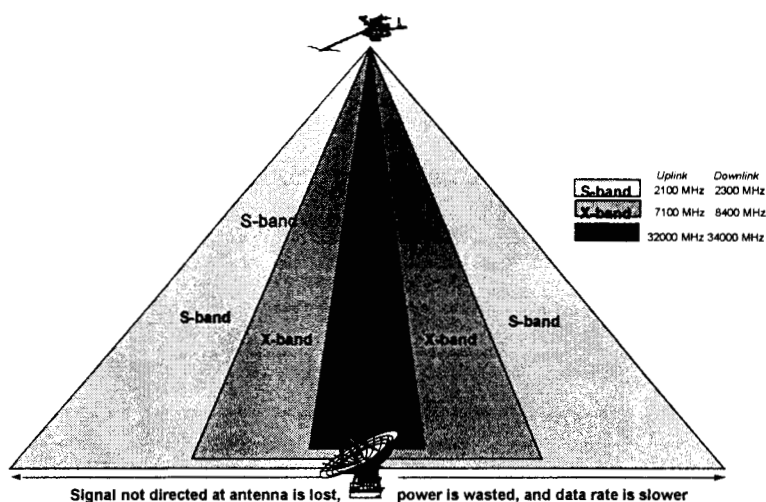


Figure 5 – Comparison of New Antennas, Ka-band Upgrade and Optical Communications

The rationale for transitioning to Ka-band is illustrated in Figure 6. As the carrier frequency increases, the width of the transmitted beam narrows, proportional to the frequency (the beam width, in radians, can be approximated by λ , the carrier frequency wavelength, divided by d , the antenna diameter). Thus, as the communications frequency transitions from X-band to Ka-band, the beam narrows by almost a factor of four and the received power per antenna surface unit is increased by almost sixteen. Unfortunately, this transition is also associated with increased degradation due to weather, antenna deformation, and reduced efficiency of components, so the typical improvement for deep space

communications is estimated at factor of four, still a remarkable improvement. If it was not for precal and postcal, a Ka-band DSN could support four times as many missions at the same data rates, or two times as many missions, at twice the data rates. To accomplish this without increasing the cost of operations will require the implementation of NSP to automate and reduce the human intervention in most of the passes.

Figure 6 – Benefits of Ka-band Communications



4. OPTICAL COMMUNICATIONS NETWORK

In the long-term, JPL plans to transition many deep space missions to optical communications. This requires development of appropriate components for both the flight and ground parts of the link as well as resolution and demonstration of significant system issues such as signal acquisition, navigation, and emergency handling. NASA and JPL are progressing in these areas and expect optical communications to become a viable option in the next decade.

5. CONCLUSIONS

To accommodate the increasing number of deep space missions, in the presence of constant or shrinking budget, JPL has developed, and is implementing, a cost-effective solution consisting of NSP, Ka-band reception upgrades, and an eventual optical communications network.

ACKNOWLEDGEMENTS

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